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Technical note

Influence of snow shovel shaft configuration on lumbosacral biomechanics during a load-lifting task

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Lower-back injury from snow shovelling may be related to excessive joint loading. Bent-shaft snow shovels are commonly available for purchase; however, their influence on lower back-joint loading is currently not known. Therefore, the purpose of this study was to compare L5/S1 extension angular impulses between a bent-shaft and a standard straight-shaft snow shovel. Eight healthy subjects participated in this study. Each completed a simulated snow-lifting task in a biomechanics laboratory with each shovel design. A standard motion analysis procedure was used to determine L5/S1 angular impulses during each trial, as well as peak L5/S1 extension moments and peak upper body flexion angle. Paired-samples *t*-tests ($\alpha = 0.05$) were used to compare variables between shovel designs. Correlation was used to determine the relationship between peak flexion and peak moments. Results of this study show that the bent-shaft snow shovel reduced L5/S1 extension angular impulses by 16.5% ($p = 0.022$), decreased peak moments by 11.8% ($p = 0.044$), and peak flexion by 13.0% ($p = 0.002$) compared to the straight-shaft shovel. Peak L5/S1 extension moment magnitude was correlated with peak upper body flexion angle ($r = 0.70$). Based on these results, it is concluded that the bent-shaft snow shovel can likely reduce lower-back joint loading during snow shovelling, and thus may have a role in snow shovelling injury prevention.

1. Introduction

Nearly 12,000 individuals are treated in U.S. emergency departments each year for snow shovelling-related injuries (Watson et al., 2011). The most common anatomical region for shovelling-related injury is the lower-back. Specifically, a retrospective study has shown that lower-back injuries account for 34.3% of all snow shovelling injuries, and in most cases, the injury is due to musculoskeletal overexertion, affecting soft tissues (Watson et al., 2011). Mechanically, this overexertion may be represented as increased joint loading in the lower-back. Therefore, biomechanical design of an ergonomic shovel that can decrease these joint loads may have implications for low-back injury prevention.

Perhaps the most common ergonomic snow shovel that is available for purchase is the bent-shaft shovel, which includes a downward bend in the shovel shaft. Despite the retail of bent-shaft shovels, no scientific evidence exists to support its use in terms of reducing mechanical loading at the lower-back. McGorry et al. (2003) studied bent-shaft shovels from a kinematic perspective, and found that a bent-shaft shovel significantly reduced upper body flexion when compared to the more common straight-shaft shovel. Huang and Paquet (2002) reported similar results. It has been speculated that the decrease in upper body flexion associated with bent-shaft shovel use would also decrease lumbar joint moments (McGorry et al., 2003); however, to the best of our knowledge, no study to date has tested this hypothesis.

Although peak joint moments provide an instantaneous indication of the mechanical loads that occur at a joint, they do not provide cumulative load information. For overuse injuries, such as low-back pain, a measure of cumulative loading such as angular impulse (integral of moments with respect to time) may provide more relevant information (Schipplein et al., 1990; Stefanyshyn

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et al., 2006). Therefore, the purpose of this study was to determine if a bent-shaft shovel influences angular impulses about the L5/S1 joint during a shovelling task. It was hypothesized that L5/S1 extension angular impulses would be decreased with bent-shaft shovel use compared to a straight-shaft snow shovel.

2. Methods

2.1. Subjects

Eight healthy, injury-free subjects (5 male, 3 female, mean (SD) age of 29.4 (1.7) years, height of 1.77 (0.09) m, mass of 73.5 (12.1) kg) participated in the study. All subjects had previous experience in shovelling snow, and two had used a bent-shaft shovel previously, though not regularly. All subjects held the shovel handle with their right hand, and placed their left hand further down the shaft. Subjects gave written informed consent prior to testing. Ethics approval was obtained from the University of Ottawa Research Grant and Ethics committee prior to subject recruitment.

2.2. Shovel designs

Fig. 1 shows a schematic representation of the two shovels tested in this study. When held vertically, the straight-shaft shovel was 6.5 cm taller than the bent-shaft shovel.

2.3. Procedure

Retroreflective markers were placed on each subject's feet, shanks, thighs, pelvis and torso using a modified version of Vicon's Plug-in-Gait marker set, with additional medial markers at the ankle, knee and hip. Subjects positioned themselves with each foot on a separate Kistler force platform (Kistler AG, Winterthur, Switzerland), and were then asked to shovel a 3 kg sand bag at a self-selected speed. As they shovelled, seven Vicon MX13 cameras (Vicon, Centennial, Colorado) recorded the 3D positions of each marker at a sampling rate of 200 Hz, while each force platform simultaneously sampled ground-reaction force data at a frequency of 2000 Hz.

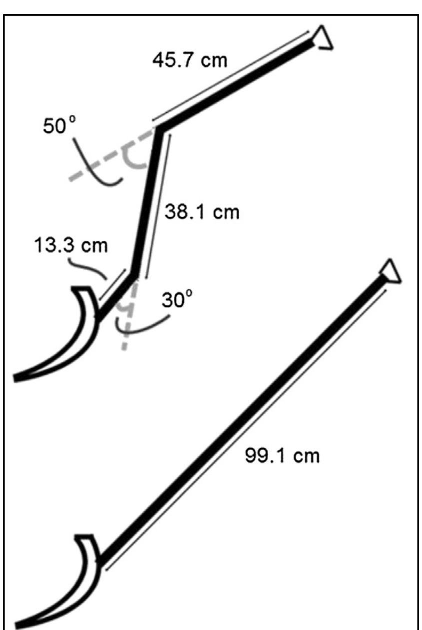

Fig. 1. Schematic showing dimensions of the bent-shaft and straight-shaft snow shovels tested in this study. The mass of the bent-shaft shovel was 1.8 kg; the mass of the straight-shaft shovel was 1.9 kg.

Subjects completed 5 trials with each shovel design in a randomly assigned order, and were provided with a 1 min break between each trial to prevent fatigue. Subjects were asked to shovel at a similar speed in each trial, and use the same hand positioning throughout. Trials began when subjects initiated trunk flexion towards the floor to accept the load, and trials ended once the shaft segment between both hands was parallel with the ground. The load was then dispatched to the left by rotating the shovel about its longitudinal axis, instead of excessive load throwing common to snow shovelling. Thus, this study made an attempt to isolate only the primary lifting movement associated with snow shovelling. A neutral trial was also collected from each subject where the subject stood in the anatomical position.

2.4. Data processing

Marker and ground-reaction force data were imported into Visual3D (C-Motion Inc., Germantown, Maryland) and were smoothed using low-pass filters with cut-off frequencies of 10 Hz (Arjmand et al., 2010). An 8-segment link-segment model comprising two feet, two shanks, two thighs, a pelvis and torso was created based on the neutral trial (Fig. 2). Based on the marker set, ankle, knee, hip and L5/S1 joint centres were defined (Kingma et al., 1996; Robertson et al., 2004). Segment lengths were then defined as the distance from the distal joint centre (or floor in the case of the foot segment) to the proximal joint centre. Using these lengths, the location of the segment centres-of-mass were estimated using established anthropometric guidelines (Dempster, 1955; Clauser et al., 1969; Hanavan, 1964). These anthropometric data, in combination with each subject's total body mass, allowed for estimation of individual segment masses and moments of inertia (Dempster, 1955; Clauser et al., 1969; Hanavan, 1964).

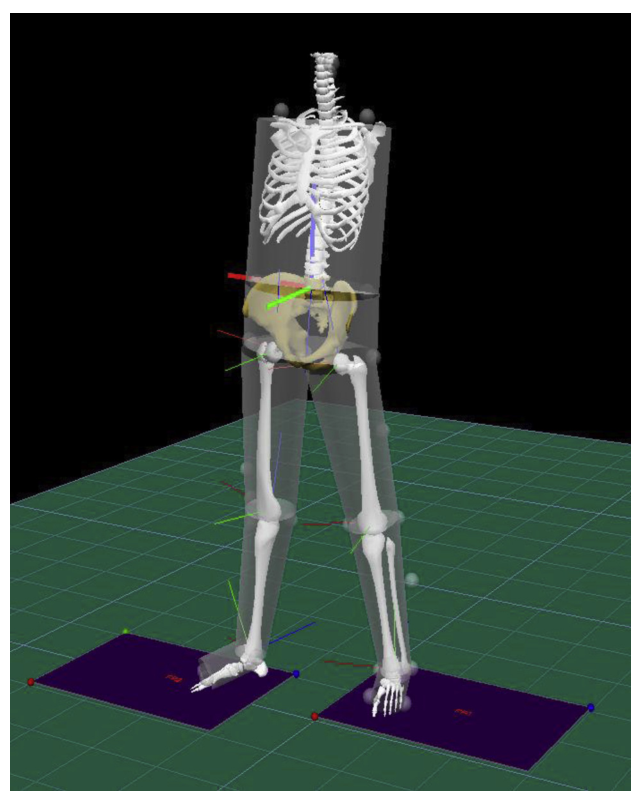

Fig. 2. 8-Segment link-segment model. Rectangles beneath the feet represent the force platform locations. The local joint coordinate systems are also shown.

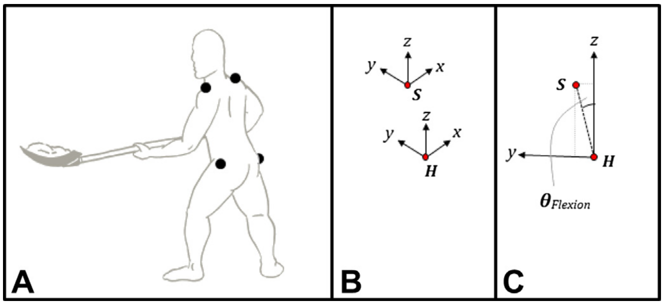

Fig. 3. The process by which upper body flexion is determined is shown. (A) Schematic of a shoveller with left and right hip and shoulder markers. (B) Taking the mean 3D positions between the two hip markers and the two shoulder markers gives virtual markers *H* and *S*. (C) Using the *y* and *z* axes, upper body flexion is calculated relative to vertical using arc tan functions.

2.4.1. Kinematics

Three-dimensional joint kinematics for the ankles, knees, hips and the L5/S1 joint were determined using a joint coordinate system (Grood and Suntay, 1983; Cole et al., 1993). Total upper body flexion was assumed to occur exclusively in the y–z plane of the laboratory and thus upper body flexion angle was calculated in 2D relative to the vertical (Fig. 3). This was done in MATLAB (MathWorks, Natick, MA) by first defining the anteroposterior (y) and vertical (z) coordinates of a point, H, midway between the right and left hip markers. A second point, S, was then defined midway between the right and left shoulder markers. Upper body flexion angle was then calculated as:

$$\theta_{\text{Flexion}} = \arctan\left(\frac{Y_S - Y_H}{Z_S - Z_H}\right) \tag{1}$$

In cases where $(Y_S - Y_H)$ or $(Z_S - Z_H)$ were equal to or less than zero, an atan2 computational programming function was used to ensure correct angle calculation. By incorporating the hips into the calculation, the flexion angle represents the total upper body flexion, with contributions from both the spine and hips.

2.4.2. Kinetics

Resultant joint moments were calculated using a Newton-Euler inverse dynamics approach (Robertson et al., 2004; Winter, 2009). In brief, joint kinetics were calculated in Visual3D for the distal joint, and then applying these kinetics to the next segment (based on Newton's 3rd law) allowed for calculation of the kinetics at the next more proximal joint. This process continued up to the L5/S1 joint, where the general form of the calculation for the L5/S1 extension moments was:

$$\begin{aligned} M_{\frac{L5}{S1_x}} = {} & \left(\begin{bmatrix} r_y \\ r_z \end{bmatrix} \times \begin{bmatrix} F_y \\ F_z \end{bmatrix}\right)_{\frac{L5}{S1}} + \left(\begin{bmatrix} r_y \\ r_z \end{bmatrix} \times \begin{bmatrix} F_y \\ F_z \end{bmatrix}\right)_{RH} \\ & + \left(\begin{bmatrix} r_y \\ r_z \end{bmatrix} \times \begin{bmatrix} F_y \\ F_z \end{bmatrix}\right)_{LH} + M_{RH_x} + M_{LH_x} - [I_x \alpha_x \\ & + (I_z - I_y)\omega_y \omega_z] \end{aligned} \tag{2}$$

where M denotes a moment, I denotes the segment mass moment of inertia of the pelvis segment at its centre of mass, α denotes the pelvis angular acceleration, ω denotes the pelvis angular velocity, r denotes a component of a 3D vector from the point of force application to the pelvis segment centre of mass, and F denotes a component of a 3D force vector. The subscripts L5/S1, RH and LH denote that the variable is with respect to the L5/S1, right hip or left hip joints, respectively. The axis about which each component acts is denoted by the subscripts x, y or z, where x is the flexion/extension axis. In MATLAB, the definite positive integral of the L5/S1 extension moments with respect to time was taken, where t_i denotes the time at which $M \geq 0$ (rising cross), and t_f denotes the time at which $M \leq 0$ (falling cross) giving the L5/S1 extension angular impulse, J:

$$J_{\frac{L5}{S1_x}} = \int_{ti}^{tf} M_{\frac{L5}{S1_x}} dt \approx \Delta t \left(\sum M_{\frac{L5}{S1_x}}\right) \tag{3}$$

Details concerning potential sources of errors associated with the processes described above are available elsewhere (Robertson et al., 2004; Winter, 2009). To account for different body proportions of subjects, moments and impulses were normalized to body mass and body height by dividing values by body mass and height [kg m].

2.5. Statistics

Two-tailed paired-samples t-tests ($\alpha = 0.05$) were performed using MATLAB to compare L5/S1 extension angular impulses, peak L5/S1 extension moments, peak upper body flexion angles, trial times, and extension moment durations between shovel conditions. To determine whether a relationship existed between peak upper body flexion angle and the peak L5/S1 extension moment, the correlation coefficient (r, $\alpha = 0.05$) between these two variables was calculated.

3. Results

Table 1 shows the main results for this study. Fig. 3 shows the mean moment–time curves and Fig. 4 shows the mean upper body flexion angle curves. The areas beneath the moment–time curves represent the angular impulses. L5/S1 extension angular impulses were significantly decreased with bent-shaft shovel use ($p = 0.022$). Specifically, the bent-shaft shovel reduced the L5/S1 extension angular impulse by 16.5% compared to the straight-shaft shovel. Seven of eight subjects experienced reduced extension impulses with the bent-shaft shovel. Trial-to-trial variability for extension impulse values for each subject was typically ±15%.

Total trial time was not significantly different between shovel conditions ($p = 0.649$; mean of 2.93 s for bent-shaft, mean of 2.86 for straight shaft); however, a trend existed (Fig. 4) where extension moment duration was reduced with the bent-shaft shovel ($p = 0.077$; extension moment for 77.5% of cycle in bent-shaft

Table 1
Aggregate lower back kinetic and kinematic results are shown for both the straight-shaft shovel and bent-shaft shovel conditions.

Variable	Straight-shaft mean (S.D.)	Bent-shaft mean (S.D.)	Mean difference[a] (95% C.I.)	p-value
L5/S1 Extension angular impulse [(N m s)/(kg m)]	1.055 (0.36)	0.881 (0.37)	−0.174 (−0.11 to −0.23)	0.022*
L5/S1 Peak extension moment [(N m)/(kg m)]	0.703 (0.21)	0.627 (0.16)	−0.083 (−0.05 to −0.12)	0.044*
Peak upper body flexion [°]	84.8 (13.3)	74.3 (11.5)	−11.01 (−8.64 to −13.4)	0.002*

Impulse and moment data have been normalized to body mass and body height as [1/kg m].
*Indicates statistical significance at $\alpha = 0.05$.
[a] Negative mean difference indicates that the variable was lower in the bent-shaft shovel condition.

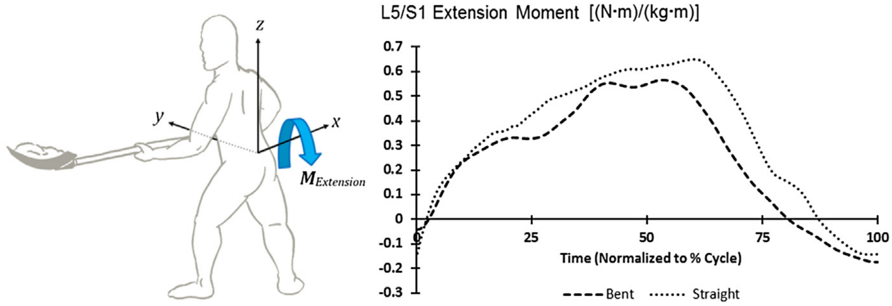

Fig. 4. Mean L5/S1 extension moment–time curves (sagittal plane) across subjects for both the straight-shaft and bent-shaft shovels.

condition; extension moment for 85.6% of cycle in straight-shaft condition).

Peak L5/S1 extension moments were significantly reduced with the bent shaft shovel ($p = 0.044$) (Fig. 4). Additionally, the peak upper body flexion angle was reduced with the bent-shaft shovel ($p = 0.002$) (Fig. 5). Peak upper body flexion angle was significantly correlated with peak L5/S1 moment magnitude ($r = 0.70$, $p = 0.0024$).

4. Discussion

The purpose of this study was to determine if a bent-shaft shovel could reduce mechanical loading at the lower-back. This research is motivated by the hypothesis that the bent-shaft shovel reduces L5/S1 extension angular impulses compared to the straight-shaft shovel. Our results support this hypothesis since reductions to L5/S1 extension angular impulses occurred with bent-shaft shovel use.

Based on kinematic data, McGorry et al. (2003) predicted that reduced upper body flexion would result in reduced lower back mechanical loads with a bent-shaft snow shovel. The present study supports this notion since the bent-shaft shovel produced lower peak upper body flexion angles which were correlated with peak L5/S1 extension moment magnitudes. Specifically, as flexion decreased, the moment also decreased. In general, greater upper body flexion was observed in the present study compared to others (Huang and Paquet, 2002; McGorry et al., 2003), potentially due to the constraints imposed by the laboratory shovelling setup, and also since contributions from the hip were included in the present study. L5/S1 extension angular impulses were reduced by about 16%, and extension moments were reduced by 11.8%, which is in agreement with McGorry et al.'s (2003) 12.9% moment-reduction estimate that was developed based on kinematic data from outdoor snow shovelling. While total trial time remained unchanged between conditions, a trend existed where the duration of the extension moment appeared to be reduced with the bent-shaft shovel. This was likely a result of the decreased flexion experienced with the bent-shaft shovel. Thus, L5/S1 extension angular impulses appear to be reduced with the bent-shaft shovel through a combination of reduced moments, and reduced moment duration via reduced upper body flexion.

Many studies have suggested that mechanical loading is a risk factor for lower-back injury (Marras et al., 1993; Watson et al., 2011). Field and laboratory studies (Huang and Paquet, 2002; McGorry et al., 2003) have shown that upper body flexion is reduced with a bent-shaft shovel, and the present study suggests that this reduced flexion also reduces loading at the L5/S1. Thus, evidence exists to support the notion that a bent-shaft snow shovel may decrease the risk of lower-back injury; however, epidemiological studies are needed for confirmation.

The present study required participants to lift the shovel load to waist height, and did not quantify loads during shovelling movements such as snow throwing, or snow pushing. Therefore, it is currently not known which shovel design is best suited for these other movements. Another limitation of this study is that participants received rest periods between each cycle to prevent muscular fatigue. While providing rest strengthens the validity of the results presented, the extent to which the results apply to true outdoor shovelling during fatiguing conditions is not known. Finally, a sand bag was used instead of snow, which may not be representative of a real load on a shovel blade when shovelling real snow. For instance, while the sand bag placed approximately even load distributions on the shovel blade, factors such as snow density gradients and the angle at which the shovel strikes the snow could influence loading distributions on the shovel blade, and consequently affect L5/S1 angular impulses. At the minimum, the results are expected to be representative of shovelling an evenly distributed load, during a non-fatigued state, when other shovelling movements are limited.

In conclusion, this study has shown that a bent-shaft snow shovel can significantly reduce L5/S1 extension angular impulses

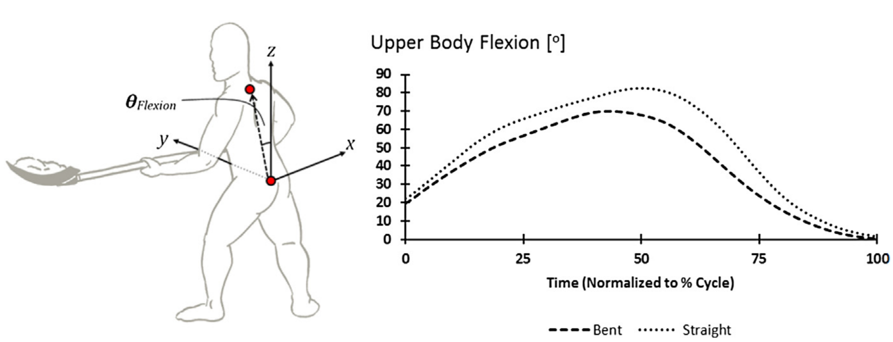

Fig. 5. Mean upper body flexion–time curves (sagittal plane) across subjects for both the straight-shaft and bent-shaft shovels.

by approximately 16% during a simulated snow-lifting task compared to a regular straight-shaft snow shovel. Additionally, these reduced loads occurred due to reduced upper body flexion. Since reduced lower-back joint loads may help prevent injury, use of a bent-shaft snow seems warranted; however, to fully understand L5/S1 joint loading during shovelling and conclusively determine the best snow shovel for injury prevention, further experiments are needed that alter some of the constraints imposed by this study.

Conflicts of interest

The authors declare no conflicts of interest.

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